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Review

Biogenic deterioration of concrete and its mitigation technologies

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HIGHLIGHTS

- Recent research has revealed important role of biogenic deterioration of concrete.
- Biogenic deterioration is a serious problem in submerged structures.
- Nanomaterials have the novel functionalities such as self-protection and anti-corrosion ability.
- This paper presents an overview of nano-enabled protection of concrete structures.
- Special focus is on biogenic deterioration and its protection.

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ABSTRACT

Concrete is used in great volumes for construction of buildings, roads, sewer systems, marine structures, bridges, and tunnels. Although chemical degradation is regarded as the major cause of their deterioration, recent research has revealed important role of biogenic deterioration. In particular, biogenic deterioration is a serious problem in sewer systems, subsea pipelines, bridge piers, oil and gas pipelines, and offshore platforms. Recently, nanomaterial-embedded concrete and nanomaterial-incorporated coatings with novel functionalities such as self-protection and anti-corrosion ability have been successfully developed for prevention and control of concrete deterioration. This paper presents an overview of both existing control measures and recent progress on development of nano-enabled approaches for protection of concrete structures against biogenic deterioration.

Contents

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1. Introduction

Deterioration of concrete occurs due to a variety of causes such as corrosion of reinforced steel and other embedded metals, alkali-aggregate reaction, freezing and thawing, and sulphate attack [1]. Corrosion of reinforced steel (loss of effective steel cross section) is considered as the dominating type of deterioration of concrete infrastructure and is usually initiated by degradation of protective concrete barrier around the steel rebar. Microbes are known to produce acids in concrete and reduce its pH. This allows the penetration of corrosion causing agents such as chlorides ions, carbon dioxide, and moisture to concrete/steel interface. The surface of the corroding steel acts as a mixed electrode, comprised of anodes and cathodes (electrically connected through the body of steel), while concrete pore water functions as an electrolyte. Depending on the pH of the electrolyte, availability of oxygen and water, relative humidity and temperature, a series of anodic and cathodic reactions occur resulting in the dissolution of metal [2].

In addition to chemical processes, durability of concrete can also be influenced by biological agents (i.e. living microorganisms). Secretion of enzymes and corrosive metabolites such as acids from microorganisms can react with the binding material of concrete surface [3]. Microbial involvement in deterioration of concrete was first reported by Parker [4], who isolated five strains of acid-producing bacteria belonging to *Thiobacillus* sp. from corroded concrete samples exposed to H_2S-rich atmosphere in sewer system. Production of sulphuric acid as a result of microbial activity and their subsequent reactions with concrete components to form expansive low-strength products is believed to be the underlying mechanism of concrete deterioration [5] that weakens the structural integrity of concrete and therefore, reduces its life [6]. Favourable conditions such as elevated relative humidity, high concentration of carbon dioxide, chloride ion or other salts, sulphates, and small amounts of acids (low pH) can facilitate the growth of microorganisms on the surface of concrete and thus enhance the rate of biodeterioration [7]. Over the last decades, biodeterioration (BD) has become the focus of attention due to its significant economic impact on various industries. BD has been mostly detected in sewer systems, subsea pipelines, bridge piers, oil and gas pipelines, and offshore platforms [8–11]. While no official data is available on the total cost associated with BD, it was suggested that it contributes to more than 50% of the failures in underground pipelines [12]. The cost of repair and maintenance of private and public sewage systems in Germany was estimated at about $100 billion, from which 40% of the damage was attributed to corrosion by biogenic sulphuric acid attack [13].

In the last few decades, several attempts have been made to protect concrete against BD based on the inhibition of microbial growth and metabolism. The strategies have been based upon two approaches: (1) modification of the local environment and (2) modification of concrete structure. While the focus of the former approach is on optimisation of the environmental parameter (e.g. pH and sulphate level) to minimise the microbial activity [14]; the latter approach focuses on more resistant materials through modification of the concrete mix [15–18], application of protective materials [19–21], and incorporation of antimicrobial agents such as biocides into concrete mix or the coating systems [22–25]. However, the effectiveness of some of these methods has been negatively affected due to the resistant nature of biofilms, alteration of functional properties of the coating materials by microbial degradation, or dissolution of antimicrobial agents and toxic biocides from the coatings [3,26].

Recently, advancements in nanotechnology have greatly influenced the performance of construction industry by improving the characteristics of construction materials. Nano-engineered concrete and nano-coatings are amongst the recent trends for application of nanotechnology in the prevention and control of concrete deterioration. Incorporation of nanomaterials into concrete matrix or in the coating formulations even at small quantities results in improved biodeterioration resistance and increased durability of concrete structures [27,28]. Compared to conventional bulk materials, the improved properties of nanomaterial incorporated systems may have resulted from their high surface area to volume ratio, which allows their uniform dispersion into the matrix material [29]. In addition to enhanced structural characteristics, superior antimicrobial properties have also been reported when the particle size of natural antimicrobial agents, such as silver and zinc, was reduced into nano-scale [30]. Nanoparticles (NPs) of Ag, CuO, TiO_2, and ZnO were reported to exhibit inhibitory effects against a wide range of microorganisms [31]. In the light of this, biocidal effects of some of nanomaterials such as TiO_2 and Ag nanoparticles to prevent stone materials from biological attack have been widely studied [32,33]. However, their application for mitigating the biogenic deterioration of concrete has been reported less frequently.

The main goal of this paper is to discuss the existing knowledge on the mitigation of the biologically induced deterioration of concrete, and to highlight the research challenges and research prospectives. A short review of current understanding of biogenic deterioration of concrete and cementitious materials and the key concepts to understand the BD mechanism are also included. The last section of this paper provides a review of existing control measures and recently published studies on nanotechnology based approaches for protection of concrete against BD, as well as environmental and exposure concerns about the release of nanomaterials.

2. Biogenic deterioration of concrete

2.1. The role of microorganisms

Role of microorganisms in deteriorating concrete can be classified into several mechanisms [9]: 1) Physical deterioration where material structure is affected by microbial growth or movement (e.g. physical or mechanical breaking), 2) aesthetic deterioration due to fouling (formation of biofilm), and 3) chemical deterioration due to excretion of metabolites or other substances such as hydrogen sulphide and acids which adversely affect the structural properties of material (e.g. increased porosity, weakening of the mineral matrix in the concrete structure) [8]. It is challenging to reproduce biogenic deterioration in the laboratory because pure cultures of bacteria, algae, and fungi are largely incapable of emulating the synergistic interactions of multiple species that results in a series of biochemical reactions in the biofilm [34,35]. In addition, study of concrete biodeterioration in different systems requires profound